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MASS PROPERTIES AND INERTIAL LOADING EFFECTS OF HEAD ENCUMBERING DEVICES

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ABSTRACT. The purpose of this investigation is to provide data relevant to the analytical and experimental assessment of the severity of head-neck system loading induced by the protective and performance enhancing equipment worn by today's aviator.

Mass properties of various head encumbering devices (e.g., helmets, gas masks, night vision goggles, etc.) have been measured using the automated mass properties measurement system of the U.S. Air Force Armstrong Aerospace Medical Research Laboratory (AAMRL). By using a Hybrid III anthropomorphic manikin head, results were expressed within a standard head anatomical coordinate system.

Dynamic tests were conducted on the Air Force 6-inch HYGE vertical impact facility. The repeatable half-sine carriage acceleration for the tests was a profile of 20 G peak acceleration and 50 millisecond duration. Head encumbering devices were mounted onto the Hybrid III manikin head-neck assembly to evaluate inertial loading effects.

The procedure for measuring the mass properties is presented along with locations of encumbrance centers of gravity, and principal moments and directions defined within a head anatomical coordinate system for eight different ensembles. HYGE test results of both unencumbered and eight encumbered configurations are also presented. Comparisons are made between two specific fighter gear and chemical defense configurations.

INTRODUCTION. Head/helmet mounted devices, while serving to protect and enhance the performance capabilities of the aviator, increase the inertial loading in the upper thoracic and cervical spine during high G maneuvers and ejection events. Biomechanical analysis of the inertial loading effects of these head encumbering devices requires an accurate measure of their mass properties. These consist of the mass, center of gravity location, and the magnitudes of the principal mass moments of inertia along with the associated principal directions. Techniques involving the use of differential weighing and an inverted torsional pendulum were developed to measure these mass properties. To quantitatively illustrate the increased loading due to the encumbering devices, an experimental effort was undertaken using dynamic test facilities and a mechanical head-neck system. Head accelerations and neck loads were monitored via a triaxial accelerometer and a six-axis load cell, while encumbered and unencumbered configurations were exposed to half sine +Gz impact accelerations of 20 G peak amplitude and 50 millisecond duration.

Several investigators have developed procedures for experimentally determining mass properties of different objects ranging from ejection seats to cadaver segments (References 2, 7, 8, 13), and one has developed a procedure for different types of helmets (Reference 13). These procedures are limited, however, in that they are test object specific, include inherent test object symmetry assumptions, and employ crude "hand-timing" methodologies for measuring periods of torsional pendulum oscillations. The procedure reported herein is much more general. It is fully automated, determines the complete inertia tensor of the test object, and can accommodate test objects weighing up to 450 pounds.

Performance characteristics of various mechanical head-neck systems have been studied by

numerous investigators (References 3, 5, 10, 12, 14). Most of these studies concentrated on the response of the head and neck to Gx (frontal) or Gy (lateral) impacts. Our study provides force and moment data measured at the head-neck junction during +Gz impacts of the Hybrid III anthropomorphic manikin head-neck structure. Furthermore, by comparing response variables from an encumbered configuration to those of the unencumbered, and between encumbered configurations, we are able to provide a relative assessment of the safety of each system.

METHOD.

MASS PROPERTY DETERMINATION. Mass properties were measured for various Air Force and Navy helmets, gas masks, and night vision goggle systems. The specific articles comprising the eight test configurations used in this study are listed in Table 1. The measurements were performed with the test object(s) rigidly mounted within a three-sided rectangular balsa wood box. The box provided a means to easily and securely house the test object(s), and the three orthogonal box edges were used to define a box axis system with respect to which the inertial measurements were made. The origin of this box axis system was the point at which the three outer box edges intersect.

TABLE 1. CONFIGURATION COMPONENTS
AND THEIR MASSES

CONFIGURATION NUMBER	HELMET, SIZE (MASS) (Kg)	MASK, SIZE (MASK MASS, HOSE MASS) (Kg)	OTHER (MASS) (Kg)
1	HGU-55/P, Large (1.08)	MBU-12/P, Ex. Long (0.29, 0.19)	
2	HGU-26/P, Large (1.58)	MBU-5/P, Short, Narrow (0.30, 0.18)	
3	HGU-39/P[a] X-Large (1.46)	MBU-13/P, (0.76, 0.27)	
4	HGU-55/P, Large (1.08)	AR-5, Mask-Large Cowl-Small (0.84, 0.51)	
5	HGU-39/P[b] X-Large (1.75)	NONE	ANVIS[c] (0.49)
6	HGU-35A/P[d] Large (1.67)	(Hose mass = 0.23)	
7	HGU-46/P Medium (1.10)	MBU-14(V)1/P Regular (.315, .19)	VTAS II[e] Medium (.75)
8	HGU-33/P Large (1.215)	MBU-14(V)1/P Regular (.347, .19)	Cat's Eyes[f] Mock-up (.835)

(a) HGU-39/P helmet shell--no visor.
(b) HGU-39/P: visor, boom microphone, ANVIS mount, and power pack.
(c) ANVIS: Aviator's Night Vision Imaging System binocular.
(d) U.S. Navy integrated helmet-oxygen-communication system.
(e) HGU-33/P helmet + Visual Target Acquisition System (VTAS) visor.
(f) Aluminum cat's eyes mock-up, mask fit with integral lens.

Centers of gravity are located using a classical differential weighing technique. A knife edge plate/electronic scale assembly is used for this purpose. With the weight of the test object and the distance between the knife edges known, the center of gravity position can be calculated by a sum of first moments about a knife edge. The plate is mounted horizontally onto the adjustable stand and scale surface, and the scale zeroed. The test assembly (box + test object) is then placed on the plate such that one of the box edges is positioned firmly against the chock. The first moment of the test assembly is then the scale reading of the test assembly multiplied by the blade-to-blade distance. Performing three such measurements establishes the three dimensional location of the test object center of gravity with respect to the box origin. To preserve the identity of the test object center of gravity location after it has been removed from the box, the coordinates of three test object landmarks are determined with respect to the box axis system. These landmarks are digitized using a Micro Control Systems, Inc. (Vernon, CT 06066) Perceptor, a potentiometer-based three dimensional position recorder. Three landmarks are required for the subsequent mathematical manipulation of test object inertial data among different coordinate systems.

An automated system consisting of a Space Electronics Inc. (Meriden, CT 06450) Mass Properties Instrument (Model KGR-8945, SN 7062) integrated with a Hewlett Packard (HP) 85-B computer was used to measure the inertial properties of the test objects. The main component of the Mass Properties Instrument is an inverted torsional pendulum. This pendulum is coupled to a platter that rides on a spherical gas bearing. The test assembly is mounted onto the platter; by recording the change in the pendulum's period of oscillation resulting from the addition of the test assembly, the mass moment of inertia of the test object can be calculated. This task was performed with the test assembly oriented in six predetermined attitudes, thereby obtaining the complete inertia tensor. Diagonalization of the inertia tensor performed on the HP 85-B yielded principal mass moments of inertia centered at the test object center of gravity and the direction cosine matrix of the principal axes defined with respect to the box axis system.

Results are expressed with respect to a standard anatomical coordinate system defined by anthropometric landmarks on a Hybrid III manikin head (Reference 9). The landmarks used for the axis system (sellion, right and left tragion, and right infraorbitale) are not well defined on the Hybrid III head, but were located at positions analogous to where they would be found on a human. A vector passing through the tragions, positive toward the left, is the Y axis with the origin at a point where a vector normal to the Y axis passes

through sellion. The XY plane is formed by the tragions and right infraorbitale. Z is positive up and X is positive forward. This anatomical coordinate system is depicted in Figure 1. A "wear" relationship between the test object and the head anatomical landmarks was established by digitizing the test object and the head while the ensemble was "worn" by the manikin head. All inertial measurements, however, were performed with a styrofoam head-form, ballasted when necessary with light-weight packing materials, to support the helmet and mask structures. It was assumed that the inertial properties of the styrofoam headform were negligible since it weighed only 0.19 pounds. To relate the measured inertial properties to the anatomical coordinate system, it was further assumed that the encumbering system was worn in an identical fashion by the styrofoam and by the manikin heads. The proper orientation was assured by keeping all adjustment straps taut and at the same settings, and by verifying that the distances between helmet and mask landmarks were the same. All configurations were tested with the flexible hoses of the gas masks removed. This was necessary because to accurately measure inertial properties there can be no relative motion of any component within the test fixture. The effect of the hose on head dynamics is still a point in question.
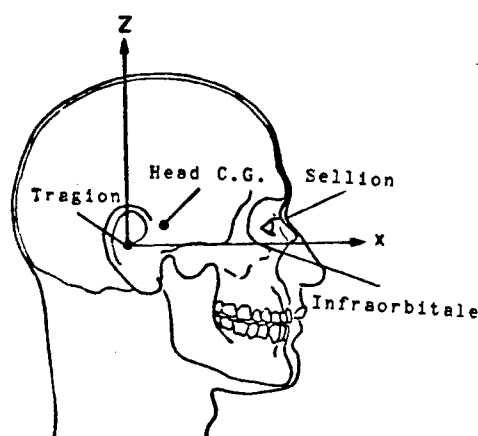

Figure 1: Head anatomical coordinate system[4].

DYNAMIC TESTING. A Humanoid Systems (Carson, CA 90746) Hybrid III 50th percentile manikin head and neck comprised the mechanical head-neck system used in this investigation. The head is constructed of cast aluminum covered with a vinyl skin and features human geometry, mass properties, and biomechanical response. The neck is constructed of aluminum plates to represent vertebral segments bonded together by alternate sections of butyl elastomer. The axial strength of the neck is enhanced by a steel cable which is bolted through the center of the neck. Saw cuts

through the elastomer on the anterior side of the Hybrid III neck provide reduced extension bending resistance without affecting flexion, and thereby replicate observed disparity in the bending resistance of an actual human neck. The damping characteristics of this neck were designed to mimic biomechanical hysteresis behavior. The head and neck are joined by a pin representing the occipital condyles. The Hybrid III neck is state of the art in terms of geometry, mass properties, and biofidelity (Reference 5).

To obtain quantitative measures of the forces, moments, and accelerations, a Robert A Denton, Inc. (Rochester, MI 48063) six-axis head transducer was positioned between the head and neck and an Endevco triaxial accelerometer package was mounted at the head center of gravity location. In addition, a triaxial accelerometer package was placed on the test carriage to verify the system's acceleration profile. Positions of fiducials mounted on the carriage, head, and helmet were recorded by high speed (500 frames/second) motion pictures and were digitized by the Automatic Film Reading (AFR) system to track relative motion. Each channel of acceleration, moment, and force data was recorded on FM tape, and strip charts of selected parameters were produced for rapid analysis and verification between tests. All of the instrumentation excitation, signal conditioning, and transmission, as well as data reduction and processing, were provided by Dynalectron Corporation.

The HYGE facility provided the 20 G peak, 50 millisecond duration, half sine acceleration versus time impact profile. This vertical impact facility consists of a 6-inch pneumatic-hydraulic actuator, a 20-foot rail system, specimen carriage, and support elements (Reference 1). Built by CVC Products, this device is located in the AAMRL at Wright-Patterson Air Force Base, Ohio. The 6-inch HYGE uses both acceleration and deceleration metering pins. The thrust is produced by differential gas pressures acting on the thrust piston. The face contour of the acceleration metering pin generates the resultant acceleration waveform. To produce an abrupt deceleration profile, the deceleration metering pin is utilized through a medium of hydraulic fluid. After the initial power thrust, the carriage coasted under 1 G of rail friction. The nitrogen-enabled carriage brakes were applied at a minimum of 350 milliseconds after the completion of the acceleration profile. Ballast weights were added symmetrically to the carriage for the various head encumbrance configurations to maintain a constant weight necessary for repeatedly generating the pulse. The interface fixture used to hold the head-neck system rigidly to the carriage

positioned the head center of gravity directly in line with the acceleration axis.

Accelerating the unencumbered mechanical head-neck system provided a baseline to which the encumbered configurations were compared. Of the configurations tested and reported, two categories can be delineated--fighter gear and chemical defense. The two fighter gear configurations investigated consisted of the HGU-55/P helmet combined with the MBU-12/P mask and the HGU-26/P helmet with the MBU-5/P mask. Chemical defense configurations were the HGU-55/P helmet and the AR-5 mask and an uncommon but accepted combination of the HGU-39/P helicopter helment and the MBU-13/P firefighter's mask. Effects of these mass additions on the dynamic response of the system were determined with and without their respective hoses.

RESULTS. As an aid in visualizing how the addition of the various encumbrances shift the effective head center of gravity position, the encumbrance ensemble center of gravity is located with respect to the head center of gravity and presented in Table 2.

TABLE 2. CONFIGURATION MASSES AND CENTER OF GRAVITY LOCATIONS WITH RESPECT TO THE HEAD CENTER OF GRAVITY

CONFIGURATION	MASS (Kg)	CENTER OF GRAVITY LOCATION WITH RESPECT TO HEAD CG (cm)		
		X	Y	Z
Head	4.54	0.00	0.00	0.00
1	1.37	-1.79	0.08	-1.42
2	1.88	-1.25	0.04	-0.31
3	2.22	-1.13	-0.18	-1.88
4	1.92	-1.96	0.60	-3.87
5	2.24	1.03	0.19	2.26
6	1.67	-3.31	1.06	-0.47
7	2.17	-3.29	-0.11	1.82
8	2.42	2.89	0.57	0.62

The reference system in which these results are presented is parallel to the head anatomical system but centered at the head center of gravity. The head center of gravity is located 3 inches posterior, and one-half inch inferior to the sellion landmark (Reference 6). The head mass quoted in the figure is the Hybrid III manikin head mass.

The inertial properties of the eight configurations listed in Table 1 are presented in Table 3. Principal directions are located by yaw, pitch, and roll angles from the anatomical axis system.

Peak flexion moments about the occipital condyle pin and compressive forces from the dynamic tests involving the fighter gear and chemical defense equipment are provided in Table 4. The moment about the occipital

TABLE 3. THE INERTIAL PROPERTIES OF THE TEST CONFIGURATIONS

CONFIGURATION	INERTIAL PROPERTIES PRINCIPAL MOMENTS (Kg-cm^2)			PRINCIPAL AXES		
	X	Y	Z	YAW	PITCH	ROLL
Head	159.126	240.498	221.042	0.43	26.57	2.74
1	129.309	138.343	188.174	3.21	41.46	3.74
2	212.819	208.901	261.017	2.85	42.65	1.32
3	245.008	266.053	300.740	7.47	18.91	5.05
4	238.171	222.264	167.660	0.94	-35.32	6.70
5	175.915	338.995	373.061	-0.08	-5.77	-14.62
6	177.399	202.318	224.198	11.16	40.84	-7.57
7	209.232	229.932	322.253	-4.01	28.13	1.29
8	223.896	327.583	322.287	8.77	-13.94	-4.54

TABLE 4. MAXIMUM FLEXION ABOUT THE OCCIPITAL CONDYLE PIN AND COMPRESSION RESULTS FOR THE CONFIGURATIONS WITH AND WITHOUT HOSES

CONFIGURATION	MAXIMUM FLEXION	MAXIMUM COMPRESSION
Unencumbered	24.87 N-m	833.5 N
HGU-55/P + MBU-12/P (with hose)	25.24 N-m (26.40 N-m)	1124 N (1152 N)
HGU-26/P + MBU-5/P (with hose)	30.58 N-m (32.58 N-m)	1258 N (1212 N)
HGU-55/P + AR-5 (with hose)	30.09 N-m (29.79 N-m)	1160 N (1184 N)
HGU-39/P + MBU-13/P (with hose)	31.77 N-m (33.05 N-m)	1387 N (1373 N)

condyle pin time history for the two chemical defense configurations and the unencumbered head-neck system is provided in Figures 2 and 3. Figure 2 contains data from tests in which the hoses were not attached, and Figure 3 contains data from tests in which the hoses were attached.
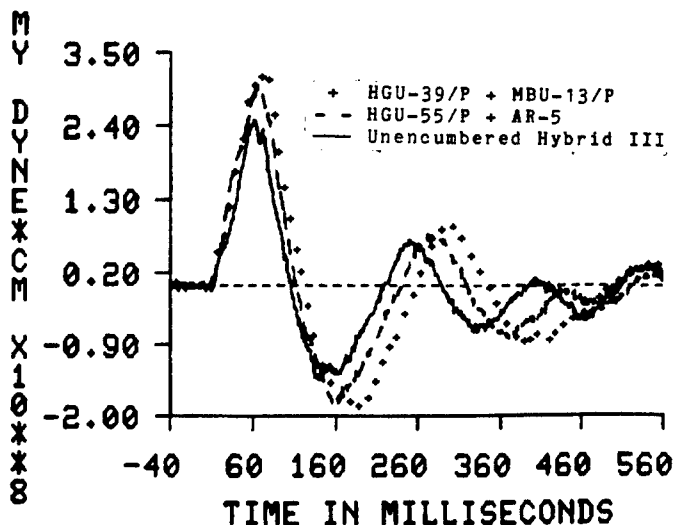

Figure 2: Moment about the Occipital condyle pin for unencumbered Hybrid III and Chem defense configurations without hoses.
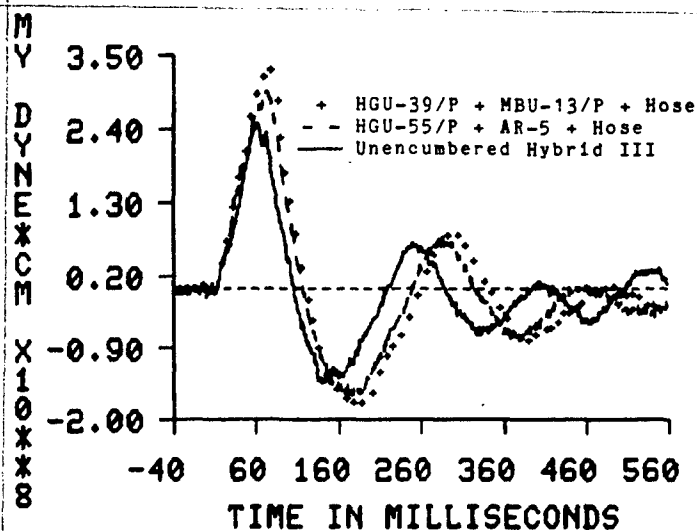
```
M
Y    3.50
D
Y    2.40        + HGU-39/P + MBU-13/P + Hose
N               - - HGU-55/P + AR-5 + Hose
E    1.30       ——— Unencumbered Hybrid III
*
C    0.20
M

X   -0.90
1
0
*   -2.00
*
*        -40   60 160 260 360 460 560
8
             TIME IN MILLISECONDS
```

Figure 3: Moment about the Occipital condyle pin for unencumbered Hybrid III and Chem defense configurations with hoses.

DISCUSSION. The accuracy of this procedure for measuring mass properties was established by measuring a precision-machined rectangular block whose actual mass properties were analytically computed. The maximum error for moments of inertia was found to be ±4 percent, maximum principal direction orientation error was ±6 degrees, and the error in locating centers of gravity was less than ±0.3 cm in each coordinate direction. Configurations 1, 2, 3, and 7 were qualitatively mid-sagittally symmetrical. A procedural check is to investigate the principal axes orientations for these configurations in light of this observation. Care was taken to fit these devices on the manikin head as symmetrically as possible. The small yaw and roll angles computed for these configurations substantiate the symmetry observation and further illustrate the accuracy of the measuring procedure. Additionally, helmet/mask nonhomogeneities contribute to these angles, leading to the suspicion that the error due to the experimental method is even less than the angles would imply.

Investigating the inertial loading effects of these head encumbrances entailed comparing the resulting flexion and extension moments and the axial compressive and tensile forces to the unencumbered head-neck values. Maximum flexion and extension moments of the unencumbered Hybrid III head and neck were 24.87 N-m and 12.84 N-m, repsectively. Axial tensile and compressive forces were 149.6 N and 833.5 N. Of the two fighter aircraft configurations tested with hoses, the HGU-26/P helmet and the MBU-5/P mask more severely loaded the head and neck system. Flexion and extension maximum values displayed an increase of 31 percent and 33 percent, while the HGU-55/P and the MBU-12/P combination increased by

6 percent and 11 percent, respectively. The HGU-26/P configuration resulted in 45 percent and 59 percent greater compressive and tensile forces than the unencumbered compared to the HGU-55/P increase of 38 percent and 9.6 percent, respectively. These results are consistent with the mass properties measured for these configurations. The HGU-26/P and MBU-5/P affect a more anterior center of gravity shift and larger principal I_y moment of inertia, both factors contributing to more severe loading during the impact, as expected.

For the two chemical defense configurations, neck flexion and extension moments were higher with the HGU-39/P and the MBU-13/P combination, exhibiting an increase of 33 percent and 20 percent, respectively. The HGU-55/P and AR-5, however, increased the flexion and extension by 20 percent and 13.5 percent. The HGU-39/P encumbrance produces greater maximum values of compression and tension as well, as much as 16 percent more than the HGU-55/P and AR-5. Again, these results are supported by the mass properties results above.

The hoses appear to represent more than just additional point masses. When added to the various head encumbrance configurations, these flexible members appear to act like springs, reducing extension moments considerably and increasing flexion moments only slightly. The hose or hoses also reduce the asymmetrical motion of the system as the elastic response absorbs energy of the input from the head-neck system.

Injury assessment values for Hybrid III neck measurements have been developed based on human volunteer and cadaver data (Reference 10). Values for flexion and extension below which significant neck injury is unlikely are 190 N-m and 57 N-m, respectively. Evaluating the largest maximum flexion and extension moments resulting from these particular configurations reveal values of 33.05 N-m and 10.14 N-m, respectively. The 20 G, 50 millisecond acceleration pulse with these encumbrance configurations excites the manikin head-neck system to an analogous level below that associated with ligamentous or vertebral damage.

CONCLUSION. An accurate automated method for measuring mass properties of head encumbering devices has been developed. Dynamic tests utilizing certain devices whose mass properties were measured, substantiate the expectation that for more drastic center of gravity shifts and larger moments of inertia, considerable increases occur in the forces and moments in the head-neck system during impact events. In terms of safety, of the two sets of fighter gear and chemical defense equipment tested, the HGU-55/P + MBU-12/P and HGU-55/P +

AR-5 appear superior to the HGU-26/P + MBU-12/P and HGU-39/P + MBU-13/P, respectively.

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BIOGRAPHIES. Jeffrey J. Settecerri joined Systems Research Laboratories, Inc., as a Biodynamic Systems Engineer in 1984 upon receiving his B.S. degree in Engineering Science/Bioengineering from the University of Michigan. His primary responsibilities in support of the AAMRL are conducting research efforts into human head-spine-torso acceleration response using the various AAMRL head-spine models, generating inertial properties data for use in conjunction with these models, and coordinating experimental efforts within the AAMRL manikin test facility. He will receive a M.S. degree in Mechanical Engineering from the University of Dayton in December 1986.

Jennifer McKenzie is the Mechanical Engineer in charge of the Manikin Development Facility. She received her B.S. in Engineering Science and Mechanics from Virginia Polytechnic and State University in 1985. Jennifer is responsible for maintaining and instrumenting the manikins for various tests involving

restraint system and head encumbrance evaluations.

Other responsibilities include calibrating the instrumentation and testing the manikins for inertial properties and joint characteristic data to be used within the Modeling and Analysis Branch of the Biodynamics and Bioengineering Division of AAMRL.

Dr. Privitzer joined the Modeling and Analysis Branch of the Biodynamics and Bioengineering Division of AAMRL in September 1979. Since that time he has been the principal investigator on all efforts concerned with the dynamic response of the human head-spine-torso structure to high G impact environments. He received his Ph.D. in Applied Mechanics from the University of Illinois in Chicago in 1979. Dr. Privitzer is a member of ASMA, AAAS, the American Society of Mechanical Engineers, and is on the organizing committee for the 6th International Conference on Mathematical Modeling.

Robert M. Beecher is Associate Research Scientist in Electrical and Computer Engineering at the University of Dayton Research Institute (UDRI). He is a 1970 graduate of the University of Virginia with a major in Anthropology and Sociology, and received his Ph.D. in Anthropology from Duke University in 1977. Before joining UDRI in 1983, he was Assistant Professor of Anatomy at Wright State University School of Medicine. His research interests include primate evolution, mammalian craniofacial biomechanics, and human body computer modeling.